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Early commercial demonstration of space solar power using ultra-lightweight arrays

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Abstract

Space solar power shows great promise for future energy sources worldwide. Most central power stations operate with power capacity of 1000 MW or greater. Due to launch size limitations and specific power of current, rigid solar arrays, the largest solar arrays that have flown in space are around 50 kW. Thin-film arrays offer the promise of much higher specific power and deployment of array sizes up to several MW with current launch vehicles. An approach to early commercial applications for space solar power to distribute power to charge hand-held, mobile battery systems by wireless power transmission (WPT) from thin-film solar arrays in quasi-stationary orbits will be presented. Four key elements to this prototype will be discussed: (1) Space and near-space testing of prototype wireless power transmission by laser and microwave components including WPT space to space and WPT space to near-space HAA transmission demonstrations; (2) distributed power source for recharging hand-held batteries by wireless power transmission from MW space solar power systems; (3) use of quasi-geostationary satellites to generate electricity and distribute it to targeted areas; and (4) architecture and technology for ultra-lightweight thin-film solar arrays with specific energy exceeding 1 kW/kg. This approach would yield flight demonstration of space solar power and wireless power transmission of 1.2 MW. This prototype system will be described, and a roadmap will be presented that will lead to still higher power levels.
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1. Introduction

The great majority of all space systems depend on solar arrays to generate electrical power to operate the spacecraft and its payloads. The current generation of scientific spacecraft beyond Earth orbit has a power limit of about 10 kilowatts of electric energy (10 kWe) at Earth's distance from the Sun (about 5 kWe at Mars distance), while commercial satellites in Earth orbit have an upper limit of about 18 kWe of electrical power. These power limitations are due to the fact that the solar arrays are but a single system of a complete satellite, generally launched on a single launch vehicle. Even the International Space Station, with a current electrical power rating of about 50–60 kWe, required three space shuttle launches to place 49,000 kg of electrical power systems into low Earth orbit, for a specific power of about 1 W/kg. Currently-available commercial technologies have a specific power of 80–100 W/kg and a mass allocation of 200 kg for a satellite in geosynchronous orbit due to launch size limitations and the specific power of current, rigid solar arrays. With these limitations, any growth in maximum power per

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satellite will be incremental—not revolutionary. A variety of technologies are being developed for higher-efficiency arrays, including triple-junction and quad-junction photovoltaic cells and spectral separation and tailoring of the photovoltaic cell for higher efficiency. These technologies offer the hope of increasing efficiency from the current levels of about 28–30% at beginning-of-life (BOL) to as much as 50%. Although these efficiency gains are impressive, they are accomplished at the cost of higher mass, so the actual specific power gains are marginal. Therefore, there will be no substantial gain in power available to spacecraft with the current generation of launch vehicles unless revolutionary improvements are made in the specific power.

Future systems will be even more sensitive to specific power. A number of conceptual design architecture studies have been performed that offer promise for terrestrial electrical power generation by space solar power (SSP), i.e. a constellation of large Earth-orbiting spacecraft that collect solar power, convert it to laser or microwave beams, and beam that power to terrestrial collectors that, in turn, convert that power to electricity [1–3]. To make this concept economically attractive, they must compete with current large power plants by economically generating Gigawatts (GW) of power. At 100 W/kg, such a power station must weigh $2–5 \times 10^7$ kg or more—a tall order for launch vehicles that currently place no more than $2–3 \times 10^3$ kg into geosynchronous orbit.

Recent technology advances in the area of thin film photovoltaic arrays offer a solution to the mass limitations of high power arrays. Thin-film arrays, while the efficiency is only around 9–12%, are so lightweight that they offer specific powers in excess of 1000 W/kg—a factor of 10 or more above the current state-of-the-art. Since these arrays are deployable, they can be packaged with minimum mass and volume, and readily deployed in space with near-term demonstrable technologies. This section provides an introduction to this possibility. The next section will discuss the specific advantages of lightweight arrays. Section 3 will describe near-term applications in the 50–500 kWe power range, both in space and in the high altitude atmosphere, as well as future directions for space power satellites and high power electric thrusters. Section 4 discusses recent and ongoing plans for prototype testing of thin-film arrays in civil and military applications as well as commercial “NewSpace” applications. In Section 5, we discuss some key process steps required for commercial development of space solar power and wireless power transmission (WPT), with specific focus on the development pathway for these solar arrays. A development Roadmap is described in Section 6. A short summary is presented in Section 7, followed by references.

2. Advantages of ultra-lightweight arrays

Since the beginning of Earth-orbiting satellites, solar array technology has gone through two or three generations, and is on the verge of a new generation. Most early satellites were powered with crystalline silicon arrays, with power levels generally below about 6 kW (kWe). These silicon arrays were heavy and operated at low efficiency, i.e. the amount of power produced per unit area of solar array started around 10–12% at BOL. These crystalline silicon arrays also degraded rapidly, dropping to 8–10% efficiencies after several years in space, as a result of radiation-induced degradation of the photovoltaic silicon and atomic oxygen-induced discoloration of the cover glass which protects the silicon from these environmental factors. In the 1990s, the technology for many, if not most, satellite solar arrays converted from these original silicon arrays to compound semiconductors, which generally used gallium arsenide plus a second or third semiconductor to capture a greater share of the solar spectrum and convert it to electricity. These compound dual-junction and triple-junction semiconductors are much more resistant to radiation and more efficient, with efficiencies of 20–24%. More recently, the ability to separate different wavelengths of the solar spectrum and tailor the incident light onto a stretched lens of selected semiconductors (separating red, yellow, green, and blue wavelengths) has shown indications of efficiencies as high as 40–50% [4,5]. Yet even at this nearly theoretical limit of efficiency, the power density level will reach only 300 W/kg.

Until recently, the focus of most solar array technology development has been toward more efficient, more radiation-resistant arrays. This focus has been driven primarily by the challenge of deployment of large arrays. This challenge has limited the total array area that can be launched into space, and therefore the way to higher power arrays has been higher efficiencies. These rigid, higher-efficiency solar arrays come at the cost, however, of relatively high mass—with the best rigid arrays able to produce about 80–100 Watts per kilogram (W/kg) at 30% efficiency, and the stretched lens arrays promising about 150 W/kg but limited to a total of around 10 kW by deployment considerations.

Two dominant performance metrics in the selection of solar array technologies are this power/mass ratio (i.e. the amount of power that can be produced for each kilogram of total mass) and the volume of the stowed array as it is launched. These are important because of

Table 1
Solar array comparisons.

	Crystalline silicon	Triple junction	Scarlet (stretched lens)	CP1™/a-Si:H	CORIN/a- Si:H	CIGS
Technology readiness	Mature, in common usage	Mature, in common usage	Some flight experience	Flown in ISS, lab cells have been tested	CP1 has been flown on ISS. CP1/a-Si cells are lab tested	Lab cells have been tested
Cell efficiency at end-of-life (%)	8–10	24–30	24–30	8–9	8–9	12–14
Power density of complete array (W/kg)	20–40	80–100	350	2023 deployed	2023 deployed	500 ?
Radiation resistance	Low	High	High	Superior	Medium	High
Atomic oxygen resistance	Low	High	Unknown	Low	High	High
Scalability to large space arrays	Limited by launch volume	Limited by launch volume	Difficult because of precision deployment	Very easy	Very easy	Limited by array design
Relative cost	Low–medium	High	High	Very low	Very low	Medium

Power density for CP1/a-Si:H or CORIN a-Si:H TFSC and CIGS TFSC is calculated for a 32 kg, ultra-lightweight 20-m (400 m^2) CFRP deployment system. Under space conditions CP1/a-Si:H and CIGS are both calculated at 12.4% efficiency. Other solar cells are calculated for current state-of-the-art rigid cell deployment systems. *Tabulated values refer to AM0 and 300 K.

the mass and volume limitations on the launch vehicle that places the array into space, and the high cost of launching this limited mass and volume. Using launch vehicles available today, these limit the total power available to satellites in geostationary orbit to about 18 kWe. Higher powers will be highly desirable as the user demands for communications services continue to increase.

Recent advances in the ability to place photovoltaic materials on very thin-film substrates have produced a new generation of solar arrays. These advances allow arrays to be stowed in the launch vehicle in very compact configurations, and easily deployed to much larger arrays than have heretofore been achievable. These new, thin-film arrays are much lighter—around 1200 W/kg, including the deployment systems. Laboratory test cells have been produced by Institut de Microtechnique at the University of Neuchatel, Switzerland using LaRC™-CP1 thin-film substrates produced by SRS Technologies in Huntsville, AL that have the highest power/mass ratio on record—4300 W/kg [6]! These thin-film arrays can be stowed in a rolled or folded configuration in the launch vehicle and deployed in space by simple boom extension or roller mechanisms. A well-designed 50 kW space solar array and deployment system using rolled mechanisms with this specific power would weigh 32 kg with a payload volume the size of a suitcase. This low mass and payload volume, combined with high power density, can provide 50 kW+ space solar arrays at 25% of the cost of current rigid solar arrays.

There are two approaches to thin-film arrays: amorphous silicon (a-Si:H) and polycrystalline Cu(Ga,In)Se2 (CIGS). The Neuchatel partners have developed an array configuration that deposits amorphous silicon on SRS 6 μm-thick CP1™ polymer films, referred to as CP1/a-Si:H arrays. CIGS cells are generally deposited on 30 μm-thick metal foil substrates, a fact that assures that CIGS cells will be heavier than CP1/a-Si:H cells. Some basic comparisons between these solar arrays are summarized in Table 1.

Using deployable thin-film arrays with specific powers in excess of 1000 W/kg opens opportunities for large power levels in space. With current launch vehicles, this means that communications satellites can have 200 kWe or more in geosynchronous orbit, or that commercial platforms such as manufacturing sites or tourist destinations, can approach a MWe. With such possibilities, this technology might drive the economics of space solar power satellites (SSPS) into the profitable arena, thereby contributing greatly to a non-petroleum-based worldwide electrical power grid.

3. Applications

Deployable thin-film arrays would have immediate applications with communications satellites

and with high altitude aircraft. A 60 kWe array which can be rolled out in 20 kWe segments would greatly extend the useful lifetime of communications satellites—essentially tripling the array lifetime by rolling out 20 kWe of BOL arrays at the end of the array's useful lifetime. An alternative application would be for much higher-power communications satellites, from 50 to 200 kWe, for higher data rates or power. A unique application may also be realized for recharging mobile batteries. Such an orbiting power platform may provide a source of electrical power for very distributed demands, such as for cellular phones and laptop computers. A 200 kWe solar array would have a mass of less than 200 kg. This would make a thin-film array attractive for still higher-power commercial applications, such as orbiting hotels—with expected demands in the 250 kWe to 1 MWe—and manufacturing sites. The latter would be either for sites for in-space construction of larger platforms, or for processing of materials in the microgravity environment of space.

As the technology matures to the megawatt range, additional applications appear promising. For example, electric thrusters in the megawatt range would be attractive for human transportation to Mars and its moons. This technology can be developed in stages, perhaps using high altitude airships (HAAs) as platforms to demonstrate megawatt arrays.

As the technology for high power thin-film arrays matures, the logical next step would be solar power satellites. With a launch vehicle capable of placing 50,000 kg to geosynchronous orbit, 50 MWe platforms can be considered as building blocks for the GWe stations that would be required to provide a primary source of power for the electrical power grid.

4. Development of ultra-lightweight arrays

Recent advances in the ability to place photovoltaic materials on very thin-film substrates have produced a new generation of solar arrays. These advances allow arrays to be stowed in the launch vehicle in very compact configurations and easily deployed to much larger arrays than have heretofore been achievable. These new, thin-film arrays are much lighter—around 1200 W/kg, including the deployment systems. Problematic to most thin-film solar arrays are radiation and atomic oxygen erosion. Test solar cells are made on CP1^{TM} polyimide that is space-rated for 10 years in Geosynchronous Earth Orbit (GEO), or SRS CORIN which is the only transparent uncoated commercial polyimide that will not erode in LEO. These flexible, 6 μm thick, thin-film arrays, can be rolled or folded into a very low stowed volume in the launch vehicle configuration, and then deployed in space by simple boom extension or roller mechanisms. Such a typical 50 kW space solar array and deployment system would weigh 32 kg with a payload volume the size of a suitcase. This low mass and payload volume, combined with high power density, can provide 50 kW+ space solar arrays at 25% of the cost of current rigid solar arrays. The key technologies are ultra-thin, deployable arrays that generate power at acceptable efficiencies with high power density, and are resistant to atomic oxygen and radiation in the operational space environment.

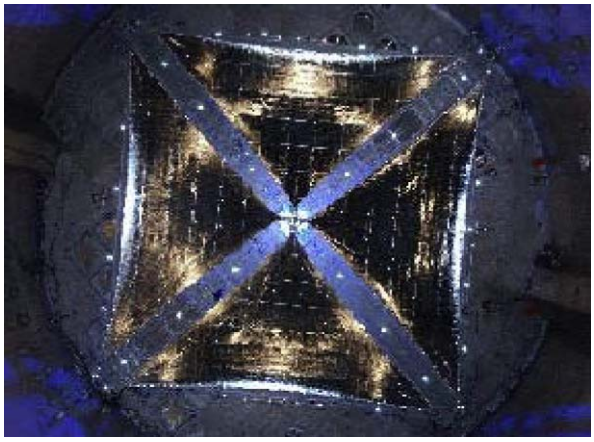

Fig. 1. Vacuum deployment of CP1 on 20-m CFRP boom at NASA Plum Brook. Photo courtesy NASA, SRS, ATK-Able.

Kayser–Threde GmbH (KT) has been working closely with the German Aerospace Center (DLR) for the last 6 years on the development, verification, and commercialization of deployable, ultra-lightweight space structures. This had led to the use of carbon-fiber reinforced polymers (CFRP) to unfold and deploy large, thin structures. This deployment technology has been demonstrated by deploying a 400 m^2 (20 m square) solar sail in a vacuum environment at the NASA Plum Brook Facility, as shown in Fig. 1. The technology is envisioned to provide a highly reliable rigidization structure for future space systems requiring large areas in excess of 100 m^2. Besides highly reliable deployment—using redundant mechanisms and actuators—this type of deployment technology offers a high degree of controllability during the deployment process. The CFRP booms deploy linearly with a slow, controllable speed of about 1 m/min.

A series of experiments have been conducted recently at the Université de Neuchatel to evaluate power

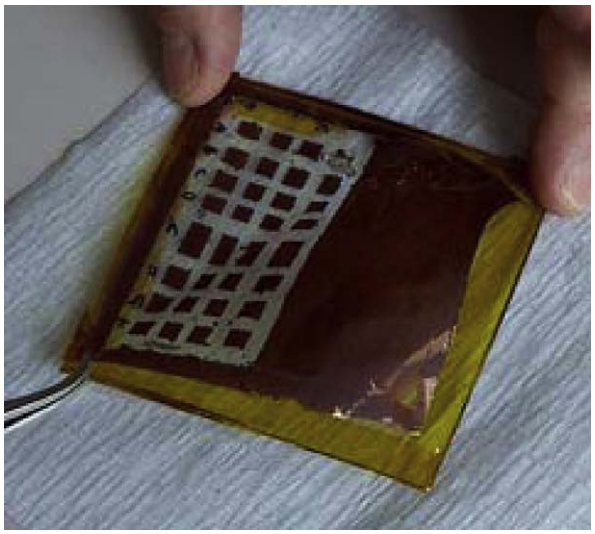

Fig. 2. a-Si:H single junction cells deposited on CP1 superstrate coated with a rough ZnO/Ag back reflector—photo IMT—Welsom Space Power Consortium.

densities that might be achievable using ultra-thin polymer films as substrates for lightweight photovoltaic materials [6]. In these experiments, amorphous silicon (a-Si:H) single-junction cells were deposited on a 6 μm fluorinated polyimide LaRC CP1^{TM} film. This film was originally developed for space applications by SRS Technologies under a NASA research and development contract, and licensed to SRS. The cells were approximately 0.25 cm^2, deposited on films that were 2–4 cm square. Such a test film is shown in Fig. 2. These cells have an areal density of 0.030 kg/m^2. In a standard air environment of AM1.5, these cells produced 95 W/m^2 power output with an efficiency of 9.5%—resulting in an AM1.5 power density of 3200 W/kg. It is estimated that these same cells should generate 4300 W/kg in vacuum, at AM0!

If a-Si:H cells can be deposited over large surface areas onto fluorinated polyimide LaRC CP1^{TM} films, then these should have similar power densities. Allowing generous losses for support equipment, cell gaps, and power losses, a gross power density in excess of 1200 W/kg should be readily achievable.

A project has been proposed to design, manufacture, and ground test a breadboard array which combines the Kayser–Threde/DLR deployment concept and advanced thin-film solar cell technology developed by the Institut de Microtechnique. This project will assess the compatibility of the KT deployment and membrane stowage concept with the CORIN/a-Si:H solar array materials. It will also perform functional, as well as environmental, tests on the breadboard model.

An early space qualification test would then demonstrate the atomic oxygen and radiation resistance in space, using 20 m square arrays, which should generate 12.5 kW of power with a total mass on the order of 10 kg.

With deployable arrays with a specific mass above 1 kWe/kg, 1 MWe would have a mass of 1 ton or less. It therefore appears quite feasible to produce space arrays in the multi-megawatt range. A standard solar array unit would be about the size of the 20-m scalable square solar sail system which was produced by SRS Technologies [7]. This array is 20 m square, for a total area of 400 m^2. Such an array should produce at least 50 kWe with a mass of 40 kg. A 100 MWe power plant would require 2000 such arrays, for a total array mass of 80,000 kg. A deployable 20 m × 20 m array has also been built for a space demonstration by Kayser–Threde [8]. This deployment is shown in Fig. 3.

The ground test ultra-lightweight CFRP 20-m boom array had a 12 μm aluminized Mylar and 7.5 μm thick aluminized Kapton polyimide, with a deployment mass of 32 kg, for an average quadrant mass of 80 g/m^2. Including current collectors and PMAD an ultra-lightweight CP1/a-Si:H 20-m CFRP boom solar array at 2 μm thickness will remain at or below this mass and provide power of 50 kWe. This configuration delivers ultra-lightweight thin-film solar cell arrays with power density ratio of 2.125 kW/kg of mass.

The larger 50-m CFRP boom array should have a mass of 30 g/m^2 as deployed in space. The 50-m CFRP boom arrays provide 2500 m^2 of active solar array at 170 W/m^2 for total deployed mass of 75 kg. This would be a 425 kWe array. This would provide a deployed array power density of 5.67 kWe/kg.

Our proposed 1.2 MWe space solar array will use four each of the ultra-lightweight 20-m CFRP boom arrays and four each of the 50-m CFRP boom arrays. The combined array made of four each of the 50-m and 20-m sub-arrays should provide 1.812 MWe at a total mass of 418 kg as deployed in space. The power density ratio for the total combined array is 4.335 kWe/kg.

Dual ultra-lightweight 150-m CFRP boom arrays have been proposed as modular structures for the European Sail Tower solar power system (SPS) Concept. These dual arrays would be connected by CFRP/graphite tri-beam truss structures with a CFRP/graphite bulkhead connective structure to adjoin up to 60 of these dual array modules, to form a 15 km long solar power satellite for microwave or laser power beaming.

Fig. 3. Deployment of an ultra-lightweight 20-m array ($400\,m^2$) at ESA/DLR European Astronaut Center in Cologne [8]. Top—CFRP booms are deployed to full 14 m length. Center—sail segments partially deployed; fans are operating to create an air cushion below the sails. Bottom—all quadrants fully deployed.

5. Commercial development of space solar power

Early commercial demonstration of space solar power systems must be based on standard business practices. Normal commercial practices must be apparent in all phases of planning, implementation, and future long-term maintenance for the SSP systems and infrastructure risk management in pursuit of this simple concept. This depends on eight process criteria, as follows.

1. A prototype design must demonstrate generous existing markets for end user products. There must be a very strong case that the SPS design can enable instant or very near-term use of wireless power transmission-enabled end-user products. Furthermore, sales of these end user products must be profitable while factoring in the costs of the early SPS demonstration prototypes.

The commercial SPS must show the probability of very good financial returns to end-user product manufacturers based on the functionality of this SPS design with these products. Miniature rectennas and MMIC chip sets, ambient microwave field recycling rectennas, and thin film polymer Fresnel rectennas are examples of advanced development technologies that can be enabled in end user consumer WPT products. These WPT technologies can be employed in products ranging from WPT rechargeable hand-held devices like cell phones, laptop computers, flat panel televisions, WPT electric automobiles, and other products with currently demonstrated large scale markets.

Remote power generation and WPT for civilian communications high altitude airships would be an example of a remarkably large near-term market enabled by commercial demonstration of SPS in space to near-space trials. Currently, long-duration, 22 km altitude HAA communications platforms that stay on station for up to a year are impossible due to mass of these on-board power storage systems. While solar cells can provide additional power during daylight hours of peak HAA communications use, only WPT can provide power at night without on-board power storage systems.

2. Manufacturing capability is critical. Ultra-lightweight carbon-fiber reinforced polymer, thin-film solar cell (CFRP TFSC) arrays provide, low payload volume and low payload mass space solar arrays that are the key enabling technology for SPS. The ability to make such solar arrays has been demonstrated at laboratory scale in the form of record power density 4300 W/kg, 9.5% stabilized efficiency AM0 (1357 standard) $122\,W/m^2$ thin-film solar cells on 6 μm thickness CP1 polyimide superstrates (polymer film towards the light).

In-space conditions offer temperatures which have been shown to self-repair a-Si cells by heat annealing. These same 6 μm thickness a-Si:H TFSC, which are 9.5% efficient under room temperature conditions, are 12.4% efficient and will provide 5950 W/kg and $170\,W/m^2$ under 100 °C space heat annealing self-repair conditions. Depositing these TFSC on 2 μm thickness CP1 or CORIN polyimide will reduce the

superstrate weight by $\frac{2}{3}$ and increase the area per kilogram of the array to approximately 100 m^2/kg. The 100 m^2 of TFSC that produces 170 W/m^2 predicts bare solar arrays with power density 17,000 W/kg.

3. There must be direct political, financial, and environmental benefits to worldwide end user populations on the ground.

4. Manufacturing methods and annual production capability must be provided with stepwise, scalable solar array systems and space deployment from MW to GW production. These scalable, modular solar arrays and deployment systems must use commercial off-the-shelf-like components wherever possible to reduce cost for re-qualification of components as stepwise upscaling of MW to GW power output and physical size of space-based WPT systems occurs.

5. All SSP systems must provide payload volume and payload mass one or two orders of magnitude lower than current state-of-the-art systems used for space power generation. This is to offset massive launch costs that would occur, using current state-of-the-art SSP systems for space-based WPT projects.

6. All solar arrays, WPT antennas, and other exposed systems must perform nominally after repeated exposure to LEO atomic oxygen environments and/or Van Allen belt radiation environments for highly elliptical quasi-geostationary (QGSO) orbits or Molniya orbits.

7. Demonstration SPS systems must be capable of power transmission of 8 h for QGSO or 12 h of power transmission for Molniya orbit from an altitude near the 1.2 MW WPT perigee, and function nominally over 10–15 years of through passage of van Allen belt radiation and LEO atomic oxygen.

8. The SPS must exhibit a maximum time frame amortization of commercial investment in the 1.2 MW array. A concept architecture for a 1.2 MWe is shown in Fig. 4. Our thin-film arrays are stored on a cartridge for launch and later deployment. Several of these arrays weigh much less than a single state-of-the-art array, so several thin-film arrays can be consecutively deployed on the SPS. Typically, space solar arrays last from 10 to 15 years. At end-of-life for the space solar array, the satellite ceases to function. At end-of-life for our thin-film array, we simply deploy a new array from a space environment-protected cartridge in place of the first.

An early commercial demonstration of SPS with a 1.2 MWe prototype must hold with the entire prerequisite we have here outlined to present a profitable business opportunity to investors and manufacturers involved with this project. The Mitsubishi SolarBird forwards the good idea of using modular space solar power satellites. These SSPs can be then made as modular components of larger power generation satellite groups and as manned capable bases from which to assemble much larger SPS array modules more along the lines of 8 MW dual solar array modules forwarded by the European Union Sail Tower SPS Concept [10]. Quasi-stationary Geosynchronous Orbit SPS can provide 8 h of WPT coverage over any metropolitan area, meaning that three of these 1.2 MWe SSPS could provide 24 h WPT service.

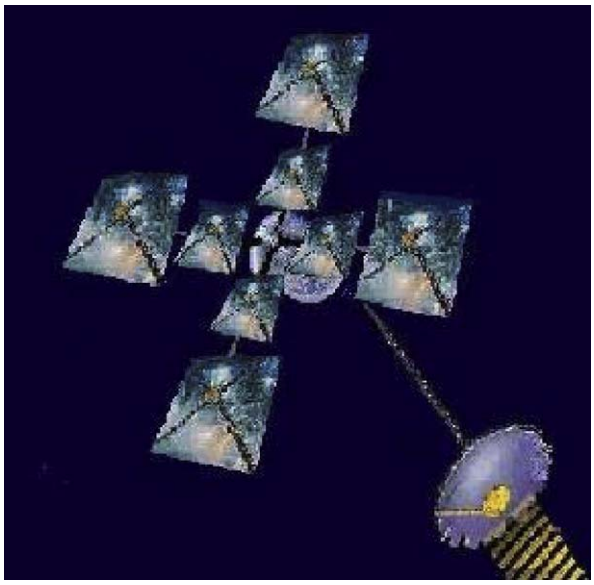

Fig. 4. The 1.2 MW made of eight CFRP boom TFSC sub-arrays. The 1.2 MW array is deployed on a manned capable inflatable space habitat with prototype 100 m microwave emitting array and 1 MW DS4G/hall electric propulsion systems.

The ultra-lightweight solar array devices are to be made as monolithically interconnected groups of 3 mm wide solar cells that are formed into 1.4 m^2 solar PV modules, which then include current collectors. The lab scale equipment used now to manufacture the record power density CP1/a-Si:H deposits a smaller 1600 cm^2 solar device that will be used in initial space testing, while the larger format 1.4 m^2 equipment is installed over the next few years.

We will use space-qualified 20-m CFRP boom systems developed by German DLR to deploy small active arrays of 2–5 kW for the first in-space testing attached to a medium-sized prototype inflatable space habitat to be launched in 2008. A full-sized polyimide quadrant will be deployed to demonstrate both the active solar array and deployment systems under LEO conditions. While only a portion of the full sized quadrant will be populated with active solar photovoltaic to test the scalable systems as a complete unit.

German DLR has space-qualified the 20-m deployment systems for solar sail deployments. German DLR and ESA made a joint study for qualification of 20-m boom for a mixed mode solar PV/solar sail propulsion system, which showed promising results. The results will be built upon by space qualifying current record power density 5580 W/kg TFSC as Welsom TFSC arrays using 20-m CFRP boom deployment systems which will each provide +50 kW of power.

The Welsom Space Power Consortium has also offered to provide space polymer expertise and exclusive CP1 and CORIN thin film polyimides to a new joint DLR–ESA study of 50-m (2500 m^2) CFRP boom deployment systems. This will space-qualify both 20-m and 50-m CFRP boom arrays by 2009–2010 when Welsom plans to begin production of 2 MW/year of space applications CP1/a-Si:H and CORIN/a-Si:H TFSC space solar array.

The 2007–2008 R&D plans at Welsom include the deposition TFSC on 2 μm thickness CP1/CORIN. TFSC on 2 μm thickness polyimide superstrates and 15.2% efficient TFSC expected under space conditions of heat annealing and self-repair, predict the manufacture of record power density solar arrays in excess of 10,000 W/kg.

6. Roadmap

Ultra-lightweight TFSC CFRP boom arrays and their space qualification and testing will provide the key technologies to drive SPS and enable the new WPT device market. The Welsom Space Power arrays will begin in-space testing in the 1 kW range on prototype inflatable habitats in 2008 and in 2009. These first in-space deployments will first use partially-populated solar PV arrays, with the balance of the array made of CP1 or CORIN polyimide thin film. This will demonstrate both the Welsom TFSC arrays and scalable CFRP boom deployment systems under space conditions.

Using currently-available industrial silicon solar cell production equipment such as KAI reactors developed by UNAXIS, Welsom will be able to manufacture 2 MW/year of space applications TFSC solar arrays by 2009–2010. We plan to provide 1.2 MW/year for each of the first three years of Welsom TFSC production to in-space demonstration of commercial SPS and testing of WPT prototype components and systems. The 1.2 MW space solar array will be comprised of four each of the CFRP 20-m array subunits and four each of the 50-m array subunits to provide an overall 1.2 MW space solar array, using commercial off-the-shelf components as shown in Fig. 5. Attached to a full-sized manned-capable inflatable space habitat with new DS4G ion thruster propulsion pods, the 1.2 MW array will provide a highly maneuverable, highly efficient base for testing both microwave and laser WPT systems in LEO and QGSO as well as lunar orbits.

The first 1.2 MW QGSO SPSs will use a smaller 100 m inflatable microwave sending antenna to demonstrate and test these systems under in-space conditions. Demonstration and studies will include space to space, space to near-space and space to ground (ocean) studies.

Space to ground (ocean) WPT will take place from LEO altitude perigee of a QSGO orbit and will demonstrate WPT beaming of uniform ambient microwave fields for WPT rechargeable devices and large rectenna systems for grid connected WPT. Hand-held device WPT components will be lab tested and tested on airship systems before the 1.2 MW array is deployed in space.

Space to near-space testing will be accomplished from both LEO altitude 500 km perigees and high altitude 40,000 km apogee of the QSGO orbit. The near-space rectennas target will be mounted in Cuben Fiber high altitude airships, called Hyperblimps. An airship consortium of comprised Dan Gerry Hyperblimp, Peter Clay Sky Solar and SESCRC, a Welsom Consortium partner, will provide WPT rechargeable Hyperblimps to low altitude civilian traffic monitoring programs in Germany during 2008–2009. Lessons learned on these low altitude WPT prototype blimp programs will be applied to 22 km altitude HAA Hyperblimps to be also made by this airship consortium. Members of this airship consortium have already succeeded in achieving powered airship flight at 22 km on three different occasions. It is believed that WPT recharge capability combined, with TFSC solar PV arrays on these HAA Hyperblimps, will enable operation of power/propulsion systems and thermal cycling mitigation measures with the use of little or no on-board power storage. This will enable existing mature technologies to be used on long endurance HAAs while generating substantial income from WPT-enabled Hyperblimps.

After demonstration and characterization of the effects of the 100 m diameter sending array, this smaller array will be retired to alternate uses and will be replaced with a full-sized 1 km diameter sending array. This full-sized 1 km array will be used to provide the commercial basis for WPT rechargeable enabled end-user products, hand-held devices, and WPT hybrid automobiles. The 1 km diameter arrays will also represent the first power generation and WPT capability to grid connected type power generation uses, as incorporated into power generation satellite groups.

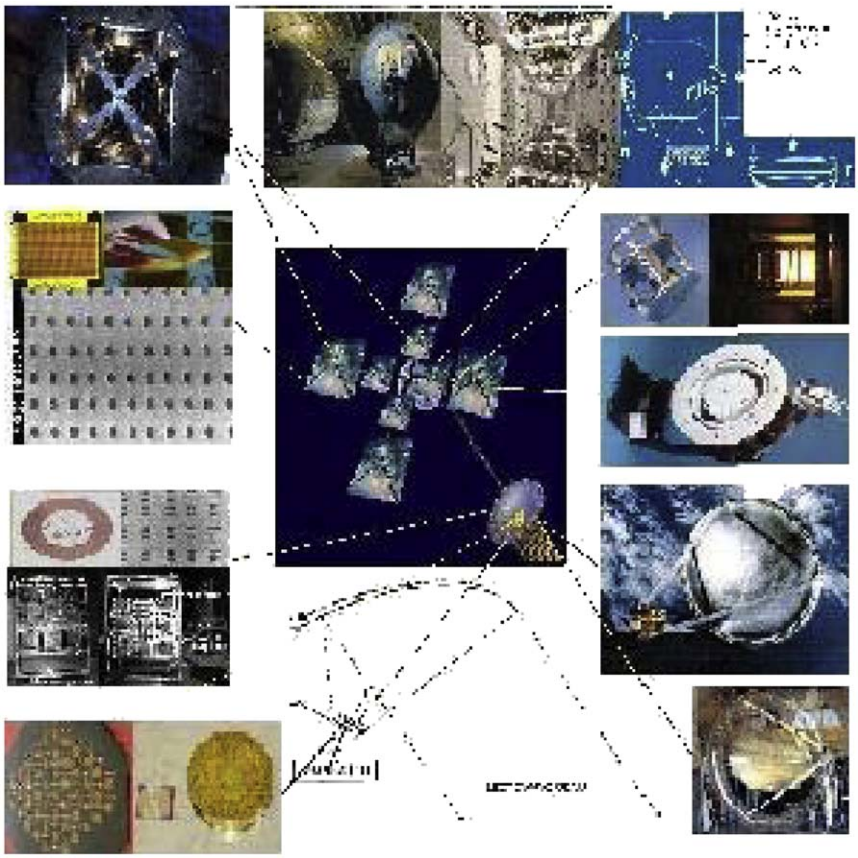

Fig. 5. COTS-like (commercial off the shelf) components for 1.2 MW SSPS array. Clockwise: Welsom ultra-lightweight CFRP boom CP1-CORIN/a-Si:H solar arrays, Bigelow manned capable inflatable space habitat, ESA-ESTEC DS4G ion thrusters, NASA hall thruster, inflatable antenna and inflatable millimeter wave reflector, offset feed horn microwave sending antenna, Mitsubishi/JAXA magnetron microwave generators, planar antennas and send/receive arrays, piezoelectric sensor/actuator resonant vibration dampers and thin film field emitters.

In the years 2012–2014, after the initial use of the 1.2 MW array, increases are planned in the manufacturing capacity of space applications TFSC to provide space arrays at the level of 8–20 MWe/year. At that time, we will begin to manufacture CFRP 150-m boom arrays with CFRP tri-beam truss structures to provide modular dual 150-m space solar array modules as forwarded by the European Sail Tower SPS Concept [10]. Each of these dual array SPS modules will provide nearly 8 MWe of power, with as many as 60–80 modules added to complete a 15 km gravity gradient stabilized array. The original 1.2 MW space solar array, with a life expectancy of 50 years, will act as the base for assembly of these sail tower dual array modules and provide propulsion from LEO where these CORIN/a-Si:H TFSC atomic oxygen tolerant arrays are assembled to the final QSGO 40,000 km stable orbits. The advent of +GW scale WPT from SPSs will begin the added use of worldwide power generation by SPS-having then reached parity cost with conventional power generation methods of oil, coal, nuclear or hydroelectric power generation [11].

Laser + PV power systems have been proposed by Boeing SpectroLab and NASA (see Fig. 6). Laser + PV prototypes would also be amenable to deployment on the 1.2 MW for in space to space, space to near-space and space to ground testing (Fig. 7). These tests could include studies from Earth or Lunar orbits.

Solar photovoltaic solar power farms. Ground based laser + PV solar farms in the square kilometer scale would not have the problems of mass add-ons and therefore could be made relatively cheaply when compared to space-based systems.

High efficiency laser + PV arrays that are tuned to discrete laser frequencies might provide a cost effective grid connected power generation when used in

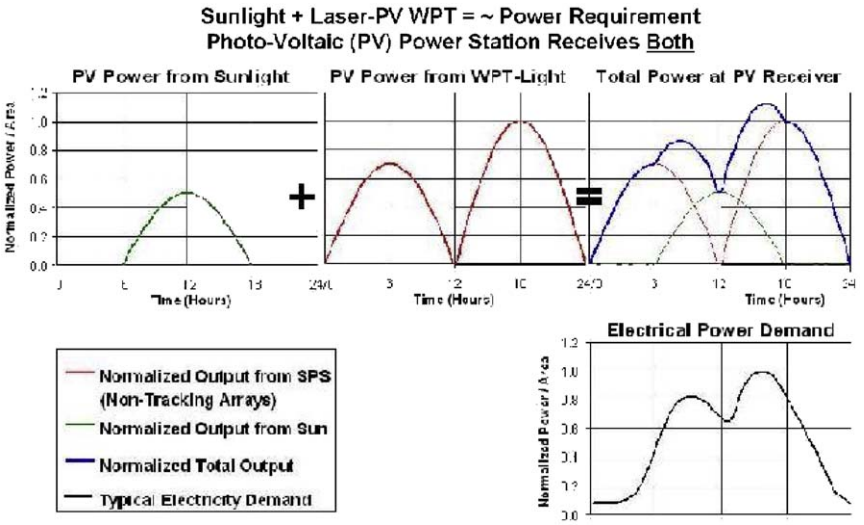

Fig. 6. Combined power output from Laser WPT–PV combined array. Courtesy NASA, Boeing.

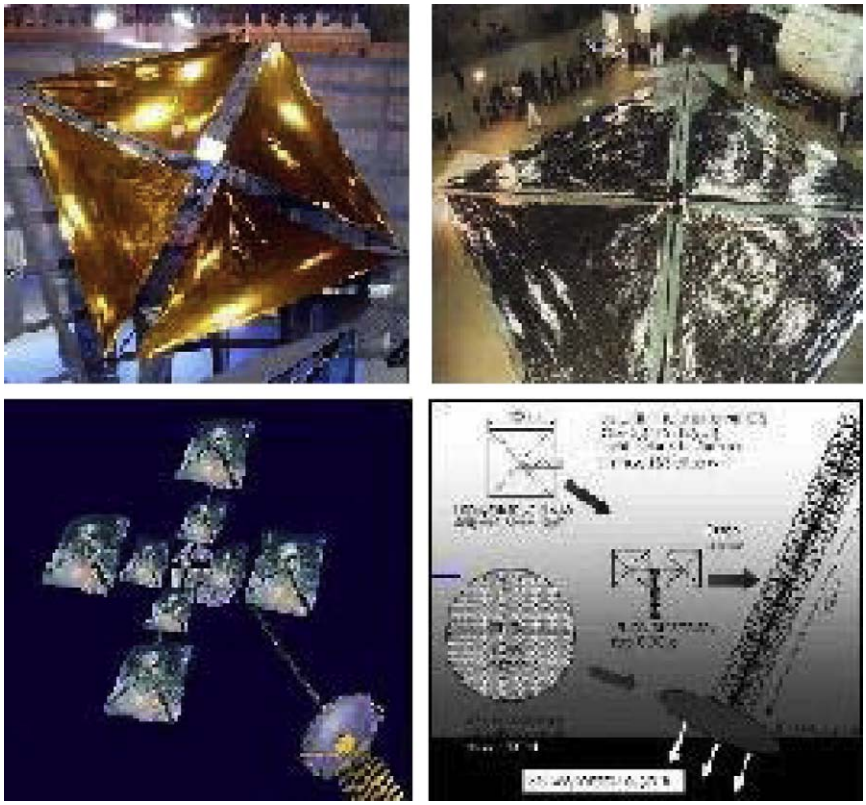

Fig. 7. Steps to SPS. Clockwise—previous 6-m breadboard array, current 20-m array, year 2010 20-m and 50-m sub-arrays on 1.2 MW on early commercial demonstration of SPS array, 8 MW twin 150-m arrays modules for European Sail Tower SPS Concept.

kilometer-sized solar farms. It has been calculated that ground based Laser + PV solar farms can provide peak power that coincides well with peak electrical usage periods (see Fig. 8).

The manned capability and general-purpose architecture of the 1.2 MW space array offer easy conversion from microwave beaming to laser beaming systems. The 1.2 MW array will provide a useful platform for

Fig. 8. The 400 MW European Sail Tower SPS Concept. Twin 150-m CFRP boom modules are the suggested next step after the scaleable 20-m and 50-m CFRP boom solar array deployments on the 1.2 MW array. Photo courtesy ESA–DLR.

demonstration of all known WPT devices. It is likely that certain configurations of both microwave and laser will be used as baseline systems and these will be improved upon during the period of the 1.2 MW commercial demonstration missions.

7. Summary

Specific power density is a critical parameter for increasing the electrical power available to spacecraft systems with launch mass constraints. Progress over the last 20 years has generally been made by increasing solar cell photovoltaic efficiency from 8–10% to 20–24%, with promising progress being made to exceed 40%. While efficiency gains improve the array area for a given power output, it does not always improve the array mass, thereby limiting the power available to commercial communications satellites with current launch vehicles to a value below 20 kWe.

Recent technology advances in the design, manufacturing, and deployment of thin film photovoltaic arrays offer a solution to the mass limitations of high power arrays. Large thin-film structures, with thickness of 6 μm and area of 400 m^2, have been built with an areal density of 0.03 kg/m^2. These films can be made from CP1^{TM} for high radiation resistance at geosynchronous orbits, or from SRS CORIN for high atomic oxygen resistance. a-Si:H solar cells have been successfully deposited by Institut de Microtechnique on CP1 substrates manufactured for solar sails by SRS technologies, with a specific power of 4300 W/kg. These thin-film arrays can be stowed in a rolled configuration and deployed in space using carbon-fiber reinforced polymers, for a total specific power (including deployment system) of 1200 W/kg or more. Even with the relatively low photovoltaic efficiency of these ultra-thin film arrays (~9–12%), a 50 kW array could easily be deployed for a total mass of 40 kg, with a stowed volume below 0.5 m^3. This would enable commercial communications satellites to have 50 kWe of power, or to roll out an extra 20 kWe whenever the original surfaces degrade to their end-of-life efficiency.

Laboratory experiments with a-Si:H cells deposited on 2 μm substrates have already demonstrated that these cells can be deposited on the ultra-thin polymer films with an efficiency high enough to achieve specific powers in excess of 1 kWe/kg. Plans are now in place for raising the technology readiness level, leading to in-space testing of kilowatt arrays within a year, followed by demonstration of 50–100 kWe arrays. This process appears to be very attractive for eventual scale-up to MWe, and then GWe solar power satellites.

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